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IMPACTS OF DAMS ON FLOW REGIMES IN THREE HEADWATER SUBBASINS OF THE COLUMBIA RIVER BASIN, UNITED STATES[1]

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ABSTRACT: We compared long-term changes in flow regimes resulting from climate change with those resulting from dams in three matched pairs of natural and modified headwater subbasins of the Columbia River. Based on the analysis of 12 flow-regime metrics, we found that damming had minimal effect on most quantity of flow metrics, but major effect on timing of flow metrics, especially those representing "spring runoff." In all modified subbasins, "spring runoff" metrics occurred much earlier than natural flow (up to ~44 days earlier for April-July flows). Storage capacity modulated the magnitude of timing of flow-metric changes, with the largest storage capacity leading to the most change. However, even in subbasins with low storage capacity, we found significant change in most timing of flow metrics. We also found that damming, especially in subbasins with higher storage capacity, overwhelmed climate variability in all basins for most flow metrics. This shows that reservoir operations need to be modified to more closely match the natural timing of flow regimes to promote positive ecologic response in modified rivers, even in basins where quantity of flow metrics have not changed substantially as a result of damming.

(KEY TERMS: dam impacts; flow regimes; flow regulation; climate change; northern Rocky Mountains.)

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INTRODUCTION

To assess the effects of dams and irrigation projects on river flow regimes, a large number of flow-regime metrics have been used to determine the change between pre- and postdam periods (Poff and Ward, 1989; Poff and Allan, 1995; Richter *et al.*, 1996; Paul and Meyer, 2001; Allan, 2004; Magilligan and Nislow, 2005; Poff *et al.*, 2007). All such studies are limited by our ability to match conditions in the pre- and postdam river, especially the same hydroclimate conditions. A central problem with comparing dammed *vs.* natural hydrographs is the need for long, continuous records that encompass the typical climate variability in a region (Arrigoni *et al.*, 2010; Greenwood *et al.*, 2011; Hirsch, 2011). Among the approaches used to examine the effects of dams on river systems that try to minimize these difficulties (Braatne *et al.*, 2008) are spatial comparisons. In spatial comparisons, we exchange the space for time, comparing hydrologic indicators in a "natural" stream

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(no or very minimal direct modification) to a "modified" stream under the same hydroclimate, over the same time period. This type of comparison can yield detailed information on how dams and other land uses modify flow regimes. The headwaters of the Columbia River basin offer an excellent locality to determine how dams affect flow regimes using this matched subbasin approach. Many headwater streams in the Columbia River basin of Montana and Idaho are relatively unaltered, with changes in flow resulting from climate change/variability alone (Stewart *et al.*, 2005; Moore *et al.*, 2007; Arrigoni *et al.*, 2010); other streams have been extensively modified (Kenny *et al.*, 2009) by dam building and irrigation development.

The Columbia River basin drains much of the northwestern United States (U.S.), is the home to numerous endangered or threatened anadromous salmonids and other aquatic species, supplies hydroelectricity, navigation, and irrigation, and derives much of its water from Rocky Mountain headwaters (Stanford *et al.*, 2005). Modification of headwater streams in the Columbia River basin started with the expansion of agriculture, logging, and mining (e.g., Anonymous, 1971; Hauer *et al.*, 2007). By the early 20th Century, gauging stations were set up to determine the best places to build more and bigger dams and plan basin-wide and inter-basin irrigation projects, producing relatively long flow records on both natural and modified streams.

We analyze daily discharge data from three representative and important headwater basins of the Columbia River: the Flathead, Boise, and Payette (Figure 1). We examine flow data from matched pairs of natural and modified subbasins in each basin, using multidecade flow records (ca. 65-90 years) that cover the variability generated by paleoclimate controls such as the Pacific Decadal Oscillation and El

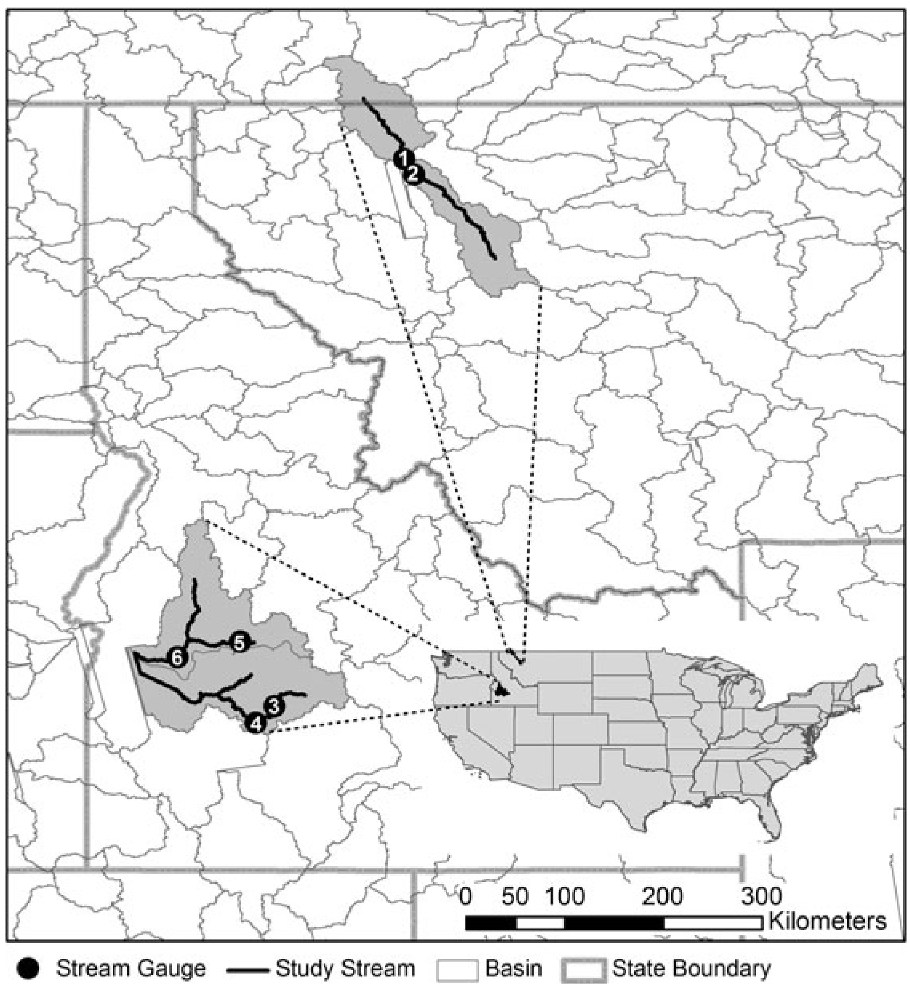

FIGURE 1. Location Map Showing Basins and Gages Used in This Study: 1, North Fork of Flathead River Near Columbia Falls, Montana (USGS 12355500); 2, South Fork of Flathead River Near Columbia Falls (USGS 12362500); 3, South Fork of Boise River Near Featherville, Idaho (USGS 13186000); 4, South Fork of Boise River at Anderson Ranch Dam (USGS 13190500); 5, Payette River at Lowman, Idaho (USGS 13235000); 6, Payette River Near Horseshoe Bend, Idaho (USGS 13247500).

Nino Southern Oscillation (Mantua *et al.*, 1997) and potential long-term trends from human-induced climate change (Stewart *et al.*, 2005; Moore *et al.*, 2007). This time period also covers the major large dam and canal construction upstream of the modified gages that occurred between 1920 and 1950 (Graf, 1999; PBS&J, 2009) and substantial increases in irrigation since 1950 (MacKichan, 1951; Kenny *et al.*, 2009). It also encompasses more recent changes in water management in response to fisheries protection or enhancement. The modified subbasins in these three basins also represent a gradient from highly modified to minimally modified, so that we can compare the role storage magnitude plays on modifying flow regimes. Finally, the relatively long records in the natural streams provide a regional snapshot of changes driven by climate change and variability in comparison with direct human modification in basins representative of snowmelt runoff in the Rocky Mountains.

METHODS

To determine suitable sites for our analysis, we reviewed the length of flow records and data on damming and other land uses. The first element of this analysis entailed selection of "matched" basins, whereby we determined the number of dams in basins throughout the Columbia headwaters, the percent area of the watershed upstream of a gage inundated by reservoirs, and the storage ratio (usable capacity of reservoir/average annual runoff). Dam information came from the Army Corp of Engineers National Inventory of Dams (NID) database, the Idaho Department of Water Resources, and the U.S. Geological Survey (Cannon and Johnson, 2004; Huo *et al.*, 2008). To select basins dominantly affected by damming and irrigation rather than urbanization, we eliminated basins with urbanized areas (see Arrigoni, 2010, for further details). This resulted in three basins to analyze: Flathead, Boise, and Payette, and six gages (one modified, one natural for each basin), all of which are described further below (Figure 1, Table 1).

To assess how flow regimes have changed in our study basins, we present a graphical analysis of 12 annual flow-regime variables. These metrics (after Poff *et al.*, 1997; Arrigoni *et al.*, 2010) were selected to represent what we consider the most important ecological and water management metrics in the study area. A broader number of metrics have been proposed elsewhere to assess hydrologic alteration (e.g., Richter *et al.*, 1996; Olden and Poff, 2003). Our 12 flow metrics include 7 that describe the quantity, 4 that describe the timing, and 1 that describes the variability. Quantity measures include the amount of flow at specific times or conditions: Q25th, Q50th, Q75th percentiles, Cum Q, Max Q, Min Q, and AMJJ Q (April-July flows); the latter is a combination of quantity and timing, but we included it with quantity. Timing metrics include the day of various flows: Day Q25th, Day Q50th, Day Q75th, and Day Max Q. Variability includes the coefficient of variation of annual flow (Coef Var).

Using these metrics allows us to compare the changes in important flow-regime components through time and how those components are modified by the gradient in reservoir storage across study basins. Plotting the time series from modified basins against those from the natural basins shows response to initial dam building as well as response to later

TABLE 1. Characteristics of Basins Studied.

Characteristic	Flathead River		Boise River		Payette River	
	Natural	Modified	Natural	Modified	Natural	Modified
USGS gage no.	12355500	12362500	13186000	13190500	13235000	13247500
Basin area (km^2)	4009	4307	1660	2533	1155	5750
Mean annual flow (m^3/s)	84.3	99.7	21.2	27.1	24.1	88.8
Mean annual flow (km^3)	2.66	3.14	0.67	0.86	0.76	2.80
Storage capacity (km^3)	None	3.68	None	0.52	None	0.26
Storage fraction	-	1.2	-	0.61	-	0.09
Maximum annual/mean annual flow	1.59	1.51	1.83	1.81	1.66	1.75
Peak/mean annual flow	23.2	13.1	10.9	10.3	10.6	8.6
Dam, date, capacity (km^3)	-	HH, 1952 (3.68) CC, 1970 (0.003)	-	AR, 1950 (0.52)	-	DR, 1930 (0.2) PL, 1942 (0.05) JK, 1973 (0.004) TJ, 1994 (0.004)

Notes: HH, Hungry Horse Dam; CC, Cedar Cr. Dam; AR, Anderson Ranch Dam; DR, Deadwood Dam; PL, Payette Lake Dam; JK, Jemima K Dam; TJ, Tom J Dam.

management decisions. The natural flow metrics in these plots act as a baseline for the modified streams, even for basins that have a very short or no predam record.

Daily flow data from the U.S. Geological Survey's National Water Information System (http://nwis.waterdata.usgs.gov/nwis, accessed April 16, 2012) for the six gages were run through a series of software scripts (MATLAB, version R2008a; The MathWorks, Inc., Natick, MA) to clean and organize the data and to calculate and analyze our 12 flow metrics. To facilitate comparisons between river basins of different sizes, all of the annual discharge flow metrics were normalized to the average value over the period of record (Q_{average} = 100%). Timing metrics were calculated as the day of the water year (Oct 1 = Day 1). We present in the text only a subsample of all the plots of all the metrics to best illustrate important changes and comparisons. All the plots and metric results are given in the Supporting Information. We present results for the gages in three forms: time series of mean daily discharge, time series of the 12 metrics, and histograms of flow metrics. In each case, we compare the natural flow-regime gage (Nat) with the modified flow-regime gage (Mod).

An unpaired *t*-test with a two-tail *p*-value (0.05) was used to test the significance of differences between means of flow-metric distributions (PRISM version 5.0b; GraphPad Software Inc., La Jolla, CA), using the null hypothesis that the modified and natural "populations" are the same and any observed difference between sample means is due to chance. In nearly all cases, the requirements for using the *t*-test were met. We present all distributions graphically, because even if the *t*-test shows that means are significantly different, there still may be substantial overlap and differences in shape that are important in interpreting differences between modified and natural flow. To compare dam-induced flow modifications with changes in flow regimes due to climate, we used linear regressions on all metrics for all natural subbasins ($p = 0.05$ was used to determine significant difference from a zero slope). The 95% confidence intervals are presented for all metric calculations to quantify the overlap shown in the plots.

Study Area

Flow regimes in all study basins (Table 1, Figure 1), and in the northern Rockies in general, are characterized by snowmelt-driven high flows between April and July and low flows in fall. For the Flathead River basin, we compare the flows measured at the natural North Fork Flathead River near Columbia Falls, Montana (FHR-Nat) with the modified South Fork Flathead River near Columbia Falls (FHR-Mod). The North Fork Flathead River, which flows from southern British Columbia into Montana and, for part of its length, borders the western edge of Glacier National Park, is unregulated. The South Fork Flathead River (FHR-Mod) was dammed by Hungry Horse Dam in 1952, 8.5 km upstream of the South Fork's confluence with the mainstem Flathead River and 2.5 km upstream of the USGS gage we analyze. Initial filling of the reservoir decreased the natural flow to nearly zero in 1952. Following reservoir filling (around three years), five distinct flow management schemes have been implemented at Hungry Horse Dam, as described by Muhlfeld *et al.* (2011), with resulting modifications of the predam hydrograph. These different postdam flow management periods have entailed changes in peaking power operations, with extreme peaking fluctuations before 1985 and a curtailment of peaking operations thereafter; implementation of minimum flows to protect kokanee (*Oncorhynchus nerka*) spawning, starting in 1982; and augmentation of late summer flows to assist outmigration of Snake River fall-run chinook salmon (*Oncorhynchus tshawytscha*), starting in 1995 (Figure 2) (Muhlfeld *et al.*, 2011).

For the Boise River basin in southwestern Idaho, we compare two gages on the South Fork Boise River. The natural South Fork Boise River near Featherville (BOI-Nat), which is located immediately upstream of Anderson Ranch reservoir, is compared with a downstream site, the modified South Fork Boise River at Anderson Ranch Dam (BOI-Mod). Construction of Anderson Ranch Dam, an irrigation and hydropower facility, was started in 1946 and completed in 1951. Only a very short predam record exists for BOI-Mod (two years). Flow management changes were implemented from the 1970s to the mid-1980s to reduce variation from natural flow and, in the 1980s, hydrographs were further modified to implement minimum flow requirements and power plant upgrades (Figure 2).

For the Payette River basin, also in southwestern Idaho, we compare the natural South Fork Payette River near Lowman, Idaho (PAY-Nat) with the modified Payette River near Horseshoe Bend (PAY-Mod). Several dams in the modified subbasin (PAY-Mod), built primarily for irrigation, regulate flow at the latter site. The largest of these are Deadwood Dam (built in 1930, on the Deadwood River) and Cascade Dam (completed in 1947, on the North Fork Payette River). Both of these dams, as well as the Anderson Ranch Dam on the South Fork Boise River, are part of the U.S. Bureau of Reclamation's Boise Project. Like Hungry Horse Dam on the South Fork Flathead, these facilities have contributed to late-summer flow augmentation for salmonid outmigration in the Snake and Columbia Rivers (Bureau of Reclamation, 2008).

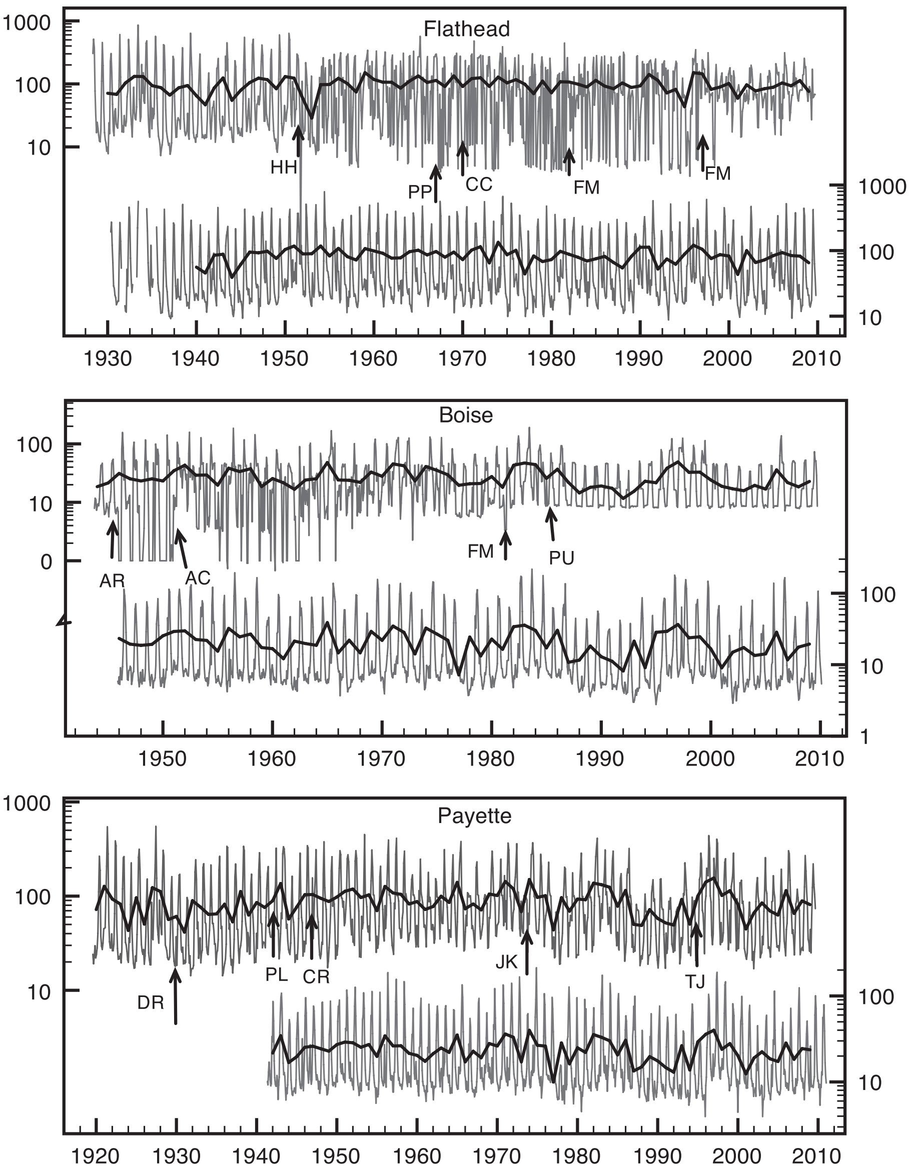

FIGURE 2. Mean Daily (gray) and Annual (black) Discharge for All Streams for Periods of Record. Upper curves are the modified subbasin and the lower curve is the natural subbasin. Arrows and labels designate major dams and other management changes that could affect flow regimes. Top: South Fork Flathead River near Columbia Falls (FHR-Mod) and North Fork Flathead River near Columbia Falls (FHR-Nat). HH, Hungry Horse Dam closed (ca. 3.7 billion m^3); CC, Cedar Creek Dam closed (ca. 3.4 million m^3 maximum storage capacity; not in SF basin, but affected HH operations); PP, major change in HH operations to produce peaking power; FM, minimum flows implemented. Middle: South Fork Boise River at Anderson Ranch Dam (BOI-Mod), and South Fork Boise near Featherville, Idaho (BOI-Nat). AR, Anderson Ranch Dam closed (ca. 522 million m^3); AC, Anderson Ranch Dam completed; FM, minimum flow regulations established; PU, power plant upgrades from 27Mw to 40Mw. Bottom: Payette River near Horseshoe Bend (PAY-Mod) and SF Payette River at Lowman, Idaho (PAY-Nat). DR, Deadwood Dam (ca. 200 million m^3); PL, Payette Lake Dam (ca. 50 million m^3); JK, Jemima K Dam (ca. 3.7 million m^3); TJ, Tom J Dam (ca. 3.6 million m^3).

RESULTS

Daily Flow Time Series

The three basins we selected for the analysis have varying levels of modification by dams and irrigation development. The Flathead River basin, in Montana, has the largest storage fraction, followed by the Boise and then the Payette (Table 1). Hydrographs from the modified subbasins in the Boise and Flathead show obvious visual differences from their natural counterparts, whereas the Payette River basin natural and modified flows look substantially similar (Figure 2).

In the Flathead, predam hydrographs from 1929 to 1951 show that FHR-Nat and FHR-Mod hydrographs were very similar, with the same maximum and minimum peaks and troughs, the same variability, and close to same flows (Figure 2). Closure of Hungry Horse Dam and subsequent changes in dam operations have produced a range of flow modifications, from reductions in natural flow to nearly zero in 1952 during initial filling of the reservoir, to periods of peaking power operations, to more recent flow releases to augment late summer Columbia River flows (compare FHR-Mod to FHR-Nat, Figure 2). From about 1996 on, modified minimum flows are much higher than natural minimum flows and the range of flows has decreased. Also the multiyear variability (few years to decadal) in flow seen in FHR-Nat is muted in the FHR-Mod hydrograph.

The Boise River basin shows the largest modification to the daily hydrograph from dam building of the three basins (Figure 2), even though the fractional amount of storage is smaller than that in FHR-Mod. Closure of Anderson Ranch Dam reduced minimum flows to zero for several years and near zero until the

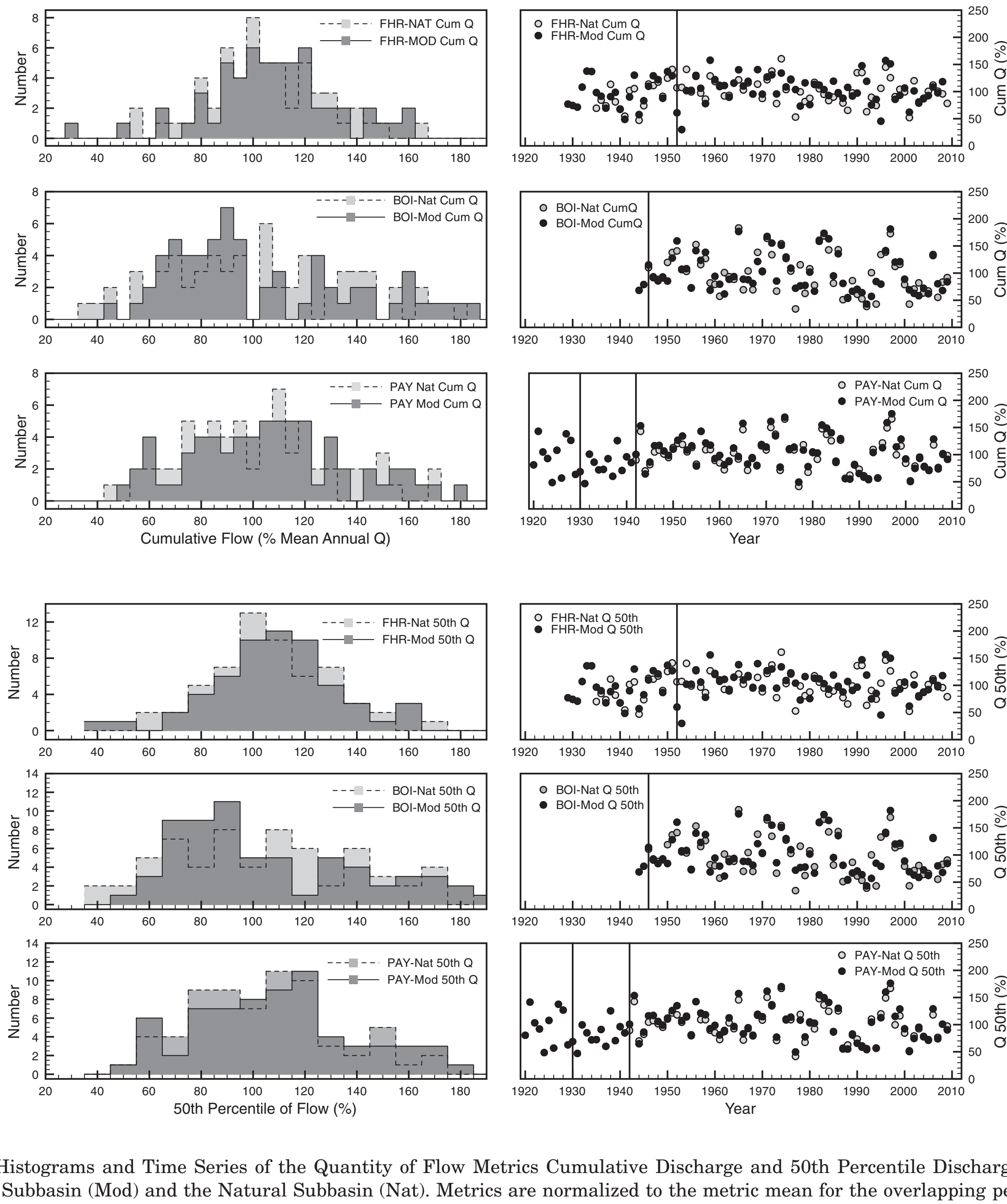

FIGURE 3. Histograms and Time Series of the Quantity of Flow Metrics Cumulative Discharge and 50th Percentile Discharge, Comparing the Modified Subbasin (Mod) and the Natural Subbasin (Nat). Metrics are normalized to the metric mean for the overlapping period of record for each basin, so are presented as % of that mean value. Vertical lines are the time of construction of large dams in the modified sub-basin (see Figure 2). As seen for Cum Q and Q 50th, similar patterns and magnitudes were found between Mod and Nat subbasins for all quantity of flow metrics (see supplementary information for all plots).

late 1960s. With changes to flow management through the 1970s to the mid-1980s, modified flow was more like the natural flow, but the range of flows was reduced substantially (Figure 2). Since 1985 minimum and maximum flows have been highly constrained and the range in flows is much smaller. Daily flow time series for BOI-Nat show several-year to decadal variability in maximum and minimum flows, whereas those patterns are minimized in the BOI-Mod hydrograph (Figure 2).

The Payette River basin has had much less modification from dam building than either the Flathead or Boise basins, with much less storage than those basins' modified sites (Table 1). As a result of this small storage capacity, the PAY-Mod daily flow hydrograph is very similar to the natural hydrograph (PAY-Nat), with approximately the same range and multiyear variability in discharge. Changes, if present, are not easily detected in daily flow hydrographs.

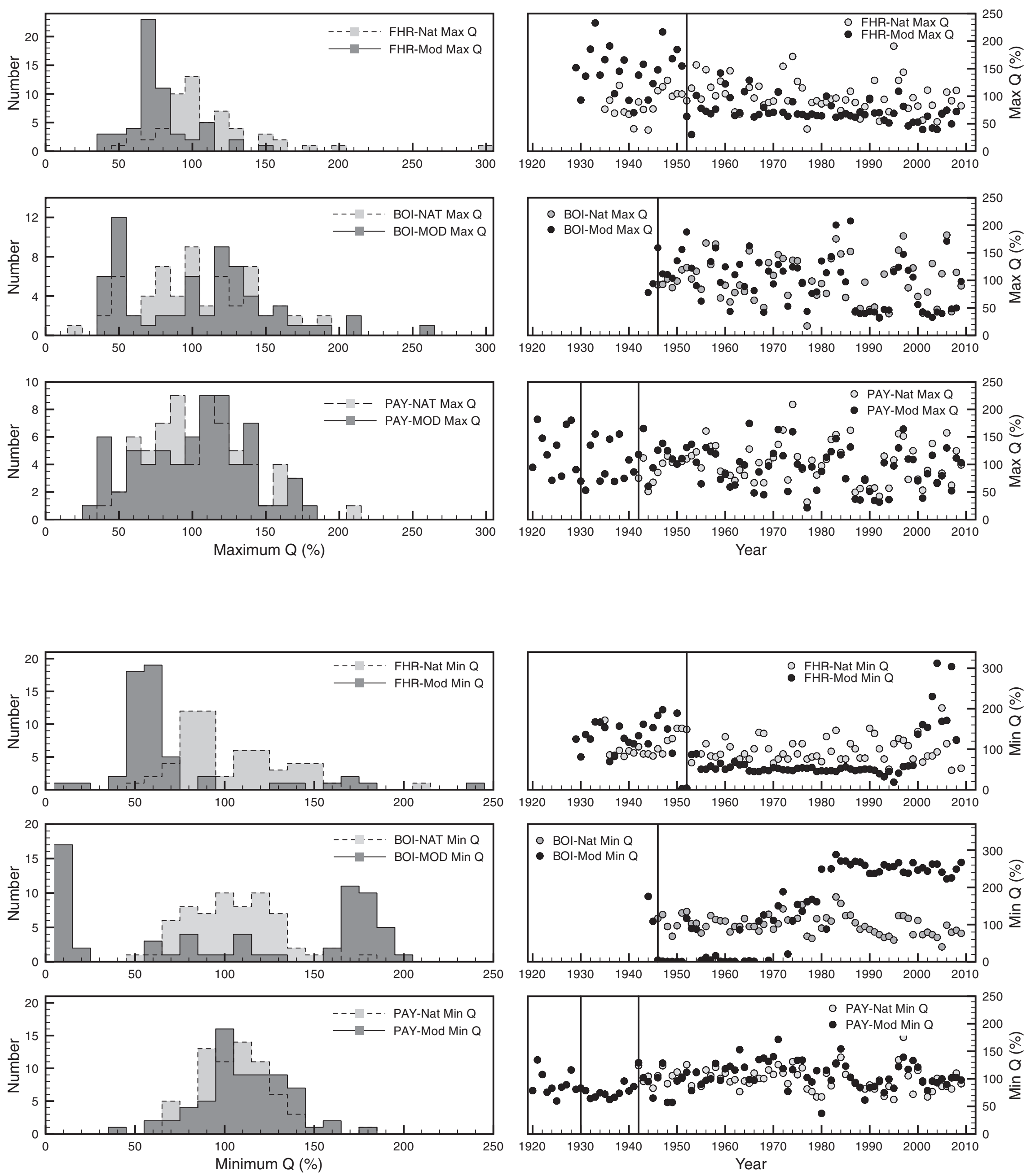

FIGURE 4. Histograms and Time Series of the Quantity of Flow Metrics Maximum and Minimum Discharge, Comparing the Modified Subbasin (Mod) and the Natural Subbasin (Nat). Metrics are normalized to the metric mean for the overlapping period of record for each basin, so are presented as % of that mean value. Vertical lines are the time of construction of large dams in the modified subbasin (see Figure 2).

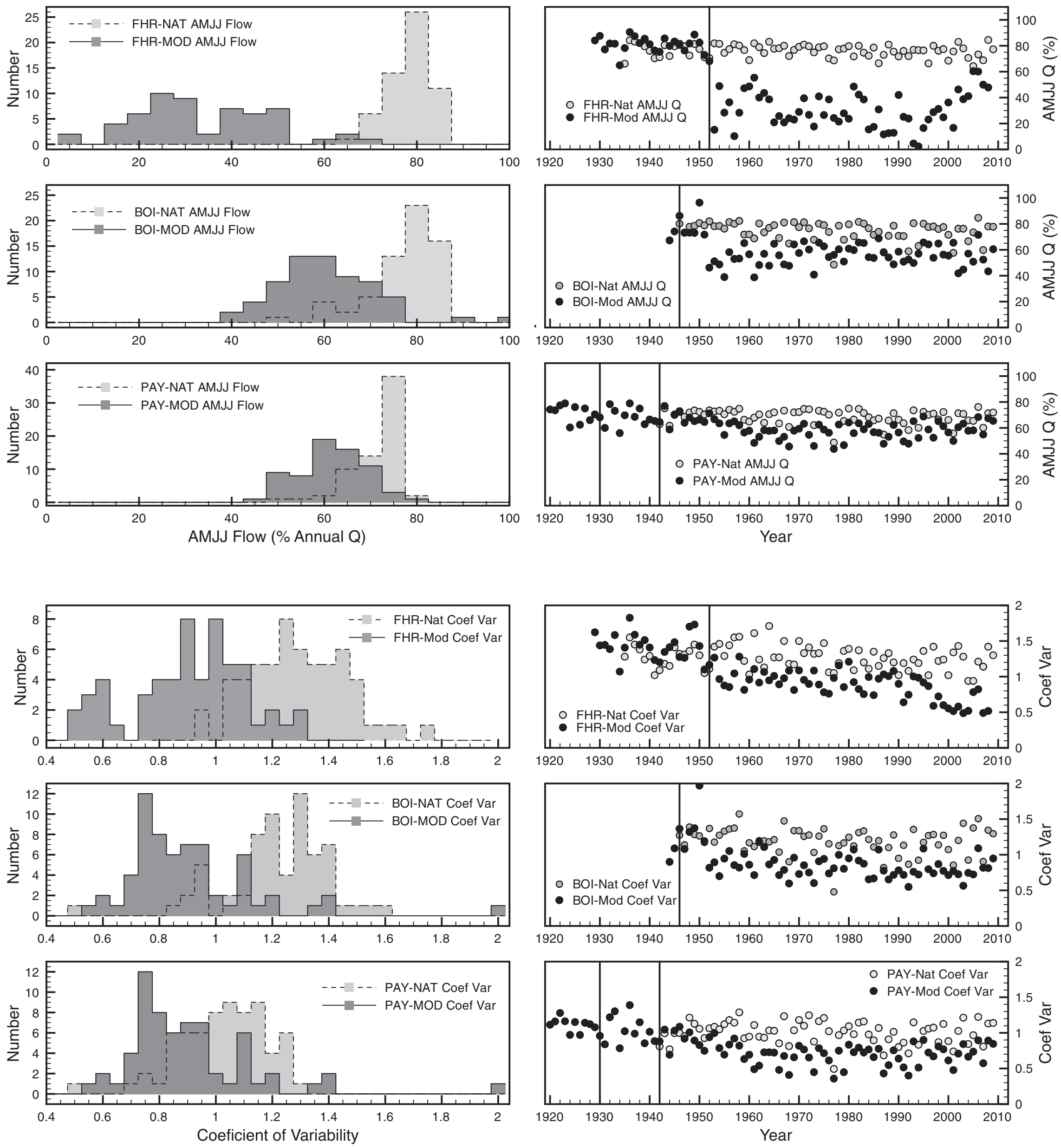

FIGURE 5. Histograms and Time Series of the Quantity of April, May, June, and July (AMJJ Q) Discharge and the Coefficient of Variability, Comparing the Modified Subbasin (Mod) and the Natural Subbasin (Nat). AMJJ Q is normalized to the metric mean for the overlapping period of record for each basin, so are presented as % of that mean value. Vertical lines are the time of construction of large dams in the modified subbasin (see Figure 2).

Flow Metric Time Series and Distributions Across a Storage Gradient

Changes to timing and variance from damming are much stronger than those to quantity. However, maximum, minimum, and AMJJ Q discharge did show substantial differences in the modified subbasins compared with the natural subbasins in most drainages. AMJJ Q, being a combination of timing and quantity and a surrogate for spring runoff, showed a very strong response to damming. Damming caused AMJJ Q to occur much earlier in the water year, and increase its variability in all three basins. Another surrogate for spring runoff, Day of 50th Q, shows similar patterns (earlier, and more variability) in two of the three basins. The magnitude of these changes varied with storage fraction in the modified subbasins (Figures 2-6; Table 2), with more storage capacity resulting in larger differences. (Plots of all 12 flow metrics are presented in the Supporting Information.)

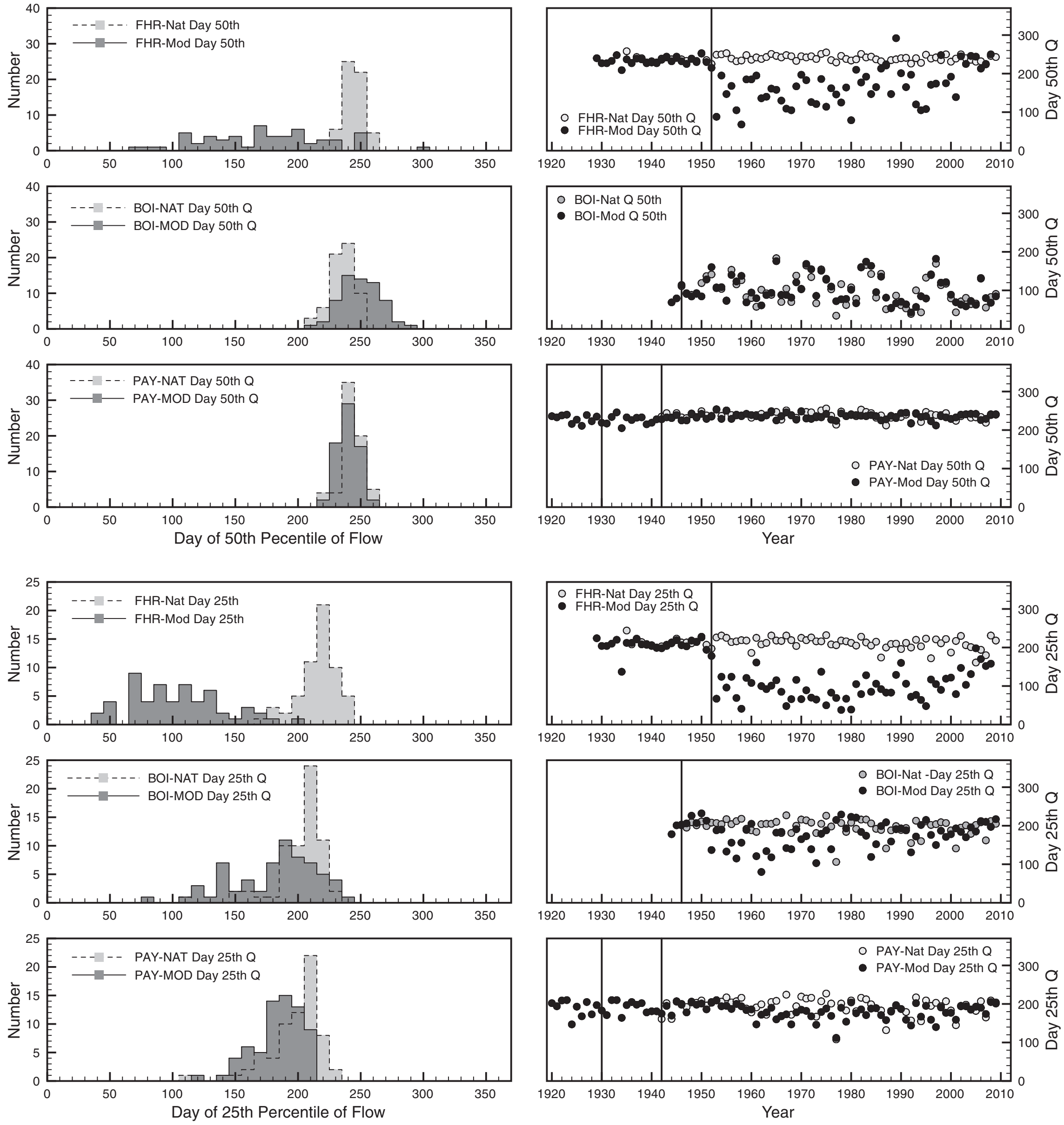

FIGURE 6. Histograms and Time Series of the Day of 50th and 25th Percentile Discharge, Comparing the Modified Subbasin (Mod) and the Natural Subbasin (Nat). Metrics in days of water year, starting October 1. Vertical lines are the time of construction of large dams in the modified subbasin (see Figure 2).

Modified Flow Metrics Compared with Natural Trends

Linear trends in flow metrics over the period of record are not statistically significant ($p > 0.05$), such that the slope of natural change cannot be distinguished from zero, for 10 of the 12 metrics in each basin. Linear trends are significant ($p < 0.05$) for 2 of the 12 metrics in each basin: Coef Var and Day Q25th in the Flathead, AMJJ Q and Min Q in the Boise, and Day Q50th and Day Q75th in the Payette (Table 3). These linear trends account for only 6-10% of variability in the time series (R^2 in Table 3), however, and are also not apparent visually in the time series plots (Figures 3-6). Nevertheless, because these six metrics show significant changes, we compare the magnitude of those linear trends with change due to damming in each of the basins.

In the Flathead basin, the trend in Coef Var in the natural flow (Table 3) would, over the 75 years of record, result in a change in Coef Var of −0.14 (Table 3), compared with a −0.39 ± 0.07 change (Table 2) due to modification over 58 years. The natural trend for Day 25th Q in the Flathead basin results in −13 days of change (Table 3), whereas the difference between natural and modified subbasins

TABLE 2. t-Test Results Comparing Means of Different Flow-Regime Metrics Between Modified and Natural Subbasins.

Metric	Flathead River Δ Mean	Flathead River p-Value	Boise River Δ Mean	Boise River p-Value	Payette River Δ Mean	Payette River p-Value
Cum Q	NSD	0.73	NSD	0.90	NSD	0.45
75th Q	NSD	0.80	NSD	0.90	NSD	0.45
50th Q	NSD	0.78	NSD	0.90	NSD	0.44
25th Q	NSD	0.81	NSD	0.90	NSD	0.44
Max Q	−31 ± 12	<0.0001	NSD	0.96	NSD	0.51
Min Q	−25 ± 18	0.006	NSD	0.990	NSD	0.15
AMJJ Q	−44 ± 4	<0.0001	−17 ± 3	<0.0001	−9.4 ± 2	<0.0001
Coef Var	−0.39 ± 0.07	<0.0001	−0.31 ± 0.07	<0.0001	−0.28 ± 0.05	<0.0001
Day Max Q	−38 ± 33	0.001	+13 ± 4	0.014	−10 ± 9	0.027
Day 75th Q	NSD	0.23	+30 ± 5	<0.0001	+13 ± 3	<0.0001
Day 50th Q	−70 ± 13	<0.0001	−14 ± 5	<0.0001	−3 ± 3	0.052
Day 25th Q	−111 ± 10	<0.0001	−20 ± 10	<0.0001	−13 ± 7	<0.0001

Notes: Difference in mean, ±95 CI (Δ Mean); negative values shows that modified subbasin is less/earlier than natural subbasin; positive shows modified is greater/later than natural. p-Value is the significance of the difference based on a two-tailed, unpaired t-test of the two distributions. NSD, not statistically significant.

was −111 days (Table 2). In the Boise basin, the natural AMJJ Q trend results in a change of only −6.5% (over 64 years), whereas the change due to modification was −17 ± 3%. However, the natural trend in Min Q results in a −28% change, whereas no change was detected between Boise natural and modified subbasins. In the Payette natural subbasin, Day 50th Q showed a linear trend resulting in a change of −8 days over 68 years, slightly larger than the −3 ± 3 days between modified and natural subbasins. Natural Day 75th Q in the Boise basin also showed a significant linear trend, resulting in −7 days of change, about half of the −14 ± 5 days difference between natural and modified subbasins.

DISCUSSION

These results show that most quantity of flow metrics are not substantially affected by damming in our study basins. Only Max Q and Min Q showed significant differences between modified and natural subbasins in the Flathead River basin, where the storage fraction was the highest. In the Boise and Payette basins where storage fraction was lower, there was no significant difference between modified and natural subbasins. In these basins, flows are managed in response to hydroclimate variation that produces quantity of flows indistinguishable from natural flows. However, in the Flathead River basin, where water managers can store a larger fraction of runoff, management has a significant effect on maximum and minimum flows, but management still does not impact the other quantity of flow metrics. These relationships hold from the beginning of modification through modern ecologic flow management schemes.

In some basins, changes in management resulted in a very different flow-regime response. This is shown best in BOI-Mod for Min Q (Figure 5). When the Anderson Ranch Dam was built, annual Min Q went to zero and reached zero most years until the mid-1970s. Then, changes in flow management in response to fisheries concerns increased flows into the natural range of Min Q. In 1980, additional management changes resulted in Min Q values much higher than natural flows and with much less variability. This resulted in a bi-modal Min Q distribution substantially different from the natural distribution. Similar responses occurred in FHR-Mod. Closing of the Hungry Horse Dam decreased Min Q to near zero for two years, and then it was maintained well below natural Min Q until 2000. Subsequent changes to aid fisheries resulted in modified Min Q flows mostly above natural Min Q flows. The most interesting aspect of these changes is that, under modern management schemes, modified minimum flows are much larger than natural minimum flows. Minimum flow releases, at the time of their original implementation, were envisioned as a means to sustain fisheries and represented an improvement in habitat conditions compared with previous management schemes. However, minimum flow releases have served to homogenize flow regimes (Poff *et al.*, 2007) in a way that does not account for the importance of flow variability for a range of aquatic species, rather than just salmonids (Poff *et al.*, 1997; Puckridge *et al.*, 1998; Lytle and Merritt, 2004; Thoms, 2006). Muhlfeld *et al.* (2011) combine the analysis of changes in flow regimes with habitat models to assess how Hungry Horse Dam operations have affected the habitat availability for native trout

TABLE 3. Statistics for Linear Regression on Natural Subbasin Flow Metrics.

	Slope	R^2	*p*-Value	Deviation from Zero?	Years	Change
Flathead						
AMJJ Q	−0.0479 ± 0.025	0.05	0.06	Not significant	75	−3.6
Cum Q	0.0130 ± 0.126	0.000	0.92	Not significant	75	0
Coef Var	−0.00191 ± 0.001	0.06	0.03	Significant	75	−0.14
Day Max Q	−0.1820 ± 0.138	0.02	0.19	Not significant	75	0
Max Q	−0.0430 ± 0.199	0.001	0.83	Not significant	75	0
Min Q	−0.0466 ± 0.158	0.001	0.77	Not significant	75	0
Day 25th Q	−0.1769 ± 0.075	0.07	0.02	Significant	75	−13
Q 25th	0.0247 ± 0.127	0.001	0.85	Not significant	75	0
Day 50th Q	−0.0273 ± 0.042	0.006	0.52	Not significant	75	0
Q 50th	0.0202 ± 0.126	0.000	0.87	Not significant	75	0
Day 75th Q	0.0058 ± 0.038	0.000	0.88	Not significant	75	0
Q 75th	0.0139 ± 0.126	0.000	0.91	Not significant	75	0
Boise						
AMJJ Q	−0.102 ± 0.047	0.07	0.03	Significant	64	−6.5
Cum Q	−0.418 ± 0.245	0.05	0.09	Not significant	64	0
Coef Var	−0.0018 ± 0.001	0.03	0.15	Not significant	64	0
Day Max Q	−0.021 ± 0.078	0.001	0.78	Not significant	64	0
Max Q	−0.220 ± 0.272	0.01	0.42	Not significant	64	0
Min Q	−0.430 ± 0.166	0.1	0.01	Significant	64	−27
Day 25th Q	−0.263 ± 0.139	0.05	0.06	Not significant	64	−17
Q 25th	−0.403 ± 0.243	0.04	0.10	Not significant	64	0
Day 50th Q	−0.110 ± 0.063	0.05	0.09	Not significant	64	0
Q 50th	−0.430 ± 0.243	0.05	0.08	Not significant	64	0
Day 75th Q	−0.086 ± 0.052	0.04	0.10	Not significant	64	0
Q 75th	−0.416 ± 0.245	0.05	0.09	Not significant	64	0
Payette						
AMJJ Q	−0.056 ± 0.034	0.04	0.10	Not significant	68	0
Cum Q	−0.211 ± 0.175	0.02	0.23	Not significant	68	0
Coef Var	−0.0008 ± 0.001	0.01	0.40	Not significant	68	0
Day Max Q	−0.126 ± 0.075	0.04	0.10	Not significant	68	0
Max Q	−0.055 ± 0.219	0.001	0.80	Not significant	68	0
Min Q	−0.214 ± 0.122	0.05	0.08	Not significant	68	0
Day 25th Q	−0.173 ± 0.136	0.02	0.21	Not significant	68	0
Q 25th	−0.206 ± 0.174	0.02	0.24	Not significant	68	0
Day 50th Q	−0.117 ± 0.055	0.07	0.04	Significant	68	−8
Q 50th	−0.210 ± 0.175	0.02	0.23	Not significant	68	0
Day 75th Q	−0.100 ± 0.041	0.09	0.02	Significant	68	−7
Q 75th	−0.209 ± 0.175	0.02	0.24	Not significant	68	0

Notes: Significance based on *p*-value of 0.05. For significant metrics, "change" is the slope multiplied by years of record; zero for nonsignificant metrics.

in the Flathead River. They find that although recent flow management more closely approximates natural flows than prior schemes, late-summer flow augmentation targeted toward anadromous salmonids further downstream in the Columbia basin reduces habitat for native fishes. The concept of "minimum flows" and their effects needs revisiting, if we are to mimic more natural hydrographs on dammed rivers.

Unlike quantity of flow metrics that mostly show minimal response to modification, timing ("day of …") and combined timing and quantity ("spring runoff" and "variability") metrics show significant and large responses to modification, even in basins with minimal storage capacity. In all modified subbasins, "spring runoff" (as shown by AMJJ Q, Day 25th, and Day 50th Q) occurred much earlier than natural flow. The amount of change scaled with storage capacity, showing that water managers used that capacity to create a much earlier spring runoff than occurs naturally. These changes were huge in the Flathead basin where AMJJ Q was advanced by 44 ± 4 days, Day 50th Q by 70 ± 13 days, and Day 25th Q by 111 ± 10 days. These values are nearly completely outside the range of natural flow variability, and as much as 10 times larger than any response to climate change seen in the few metrics that show natural trends (see figures). Changes due to damming are also substantially larger than anything reported on natural flow response to climate change (Stewart *et al.*, 2005; Moore *et al.*, 2007; Arrigoni *et al.*, 2010).

These results are relevant to attempts to elucidate how climate change has already affected flows in the western U.S., and to predicting future changes in flows, in the context of concerns for anadromous salmon and bull trout (e.g., ISAB, 2007) and for water resources planning and management (e.g., Brekke, 2011), including in the Flathead (Muhlfeld *et al.*, 2011), Boise (Bureau of Reclamation, 2008; Isaak *et al.*, 2010), and Payette (Hoekema *et al.*, 2010) basins. For example, Isaak *et al.* (2010) model potential effects of climate change on salmonid habitat in the Boise basin and suggest that bull trout habitat has already been lost as a result of warming headwater streams. In part, based on data from the Featherville (i.e., our BOI-Mod) gage, they suggest a decreasing trend in flow (as measured by annual mean flow from July 15 to September 15) from 1950 to 2006 (no r^2 reported). Our analysis does not show such a trend in any of the quantity of flow metrics in the natural subbasin of the Boise or any substantial difference between quantity of flow metrics between natural and modified subbasins. However, it is clear from our analyses that such modifications have, and will continue to have, a large effect on timing of flow metrics and associated ecological function. It is therefore critical that these direct modifications are taken into account for any new storage projects in snowmelt runoff basins.

In the area encompassing our study gages, Stewart *et al.* (2005), using simple linear regression ($p = 0.10$), found that the timing of "center of mass" flows occurred from 5 to 20 days earlier and the "spring pulse" changed from +15 to −20 days from 1948 to 2002. They ascribed that change to regional warming in response to human-induced global warming. Moore *et al.* (2007), using more complete statistical tests on data from 1951-2005 for 21 gages in the region, found that most gages had nonsignificant linear trends for "spring runoff" timing metrics (Day 25th and 50th). Those that were significant showed a trend of about −10 to −20 days, similar to what Stewart found. In this study, we found that changes due to damming (over a similar time period) were much larger than these natural trends in the most modified basin, outpacing forcing from changes in climate by 5 to 10 times.

CONCLUSION

Ye *et al.* (2003) found that, for streams in the Lena River basin (Siberia), "… reservoir regulation … significantly altered the monthly discharge regime…" above that driven by regional warming. Malmqvist and Rundle (2002) found that globally, increases in diversion and damming will be the "overriding pressure on running water ecosystems" over c. 10-15 years, whereas global change effects will play out over time spans >50 years. As we found in the northern Rocky Mountains, Shiklomanov and Lammers (2009) showed that damming had minimal effect on annual flows, and that "climate change signals were overwhelmed by human-induced river impoundments." However, we also found that the magnification of modification in spring runoff timing is definitely modulated by the storage capacity in a basin. Managers given a basin with a high storage capacity can modify (and have modified) flow metrics substantially more than those given basins with low storage capacity. This shows that as storage capacity increases in a basin, flow regimes will be pushed farther from natural conditions. Graf (2006) found that large dams throughout the U.S. with high storage fractions affected a number of flow measures and geomorphic characteristics important to river ecosystem function. Palmer *et al.* (2008) showed that highly dammed river basins are much less resilient to impacts from climate change than "free-flowing rivers." This relationship is especially important as new dams are proposed to meet increased future demand and predicted increased variability in snowmelt runoff throughout mountainous regions (Stewart *et al.*, 2005; Boxall, 2007). Even if new dams are not built, it is important to know how best to manage rivers in the face of multidecadal forcing from climate change. Reservoir operations will need to be modified to more closely match natural flow regimes in order to sustain and restore downstream riverine ecosystems (e.g., Richter *et al.*, 2003; Jager and Smith, 2008; Konrad *et al.*, 2011) and adapt flow management to promote positive ecologic response (e.g., Galat and Lipkin, 2000).

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S1. Histograms and Time Series for All Flow Metrics.

Please note: Neither AWRA nor Wiley-Blackwell is responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

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